



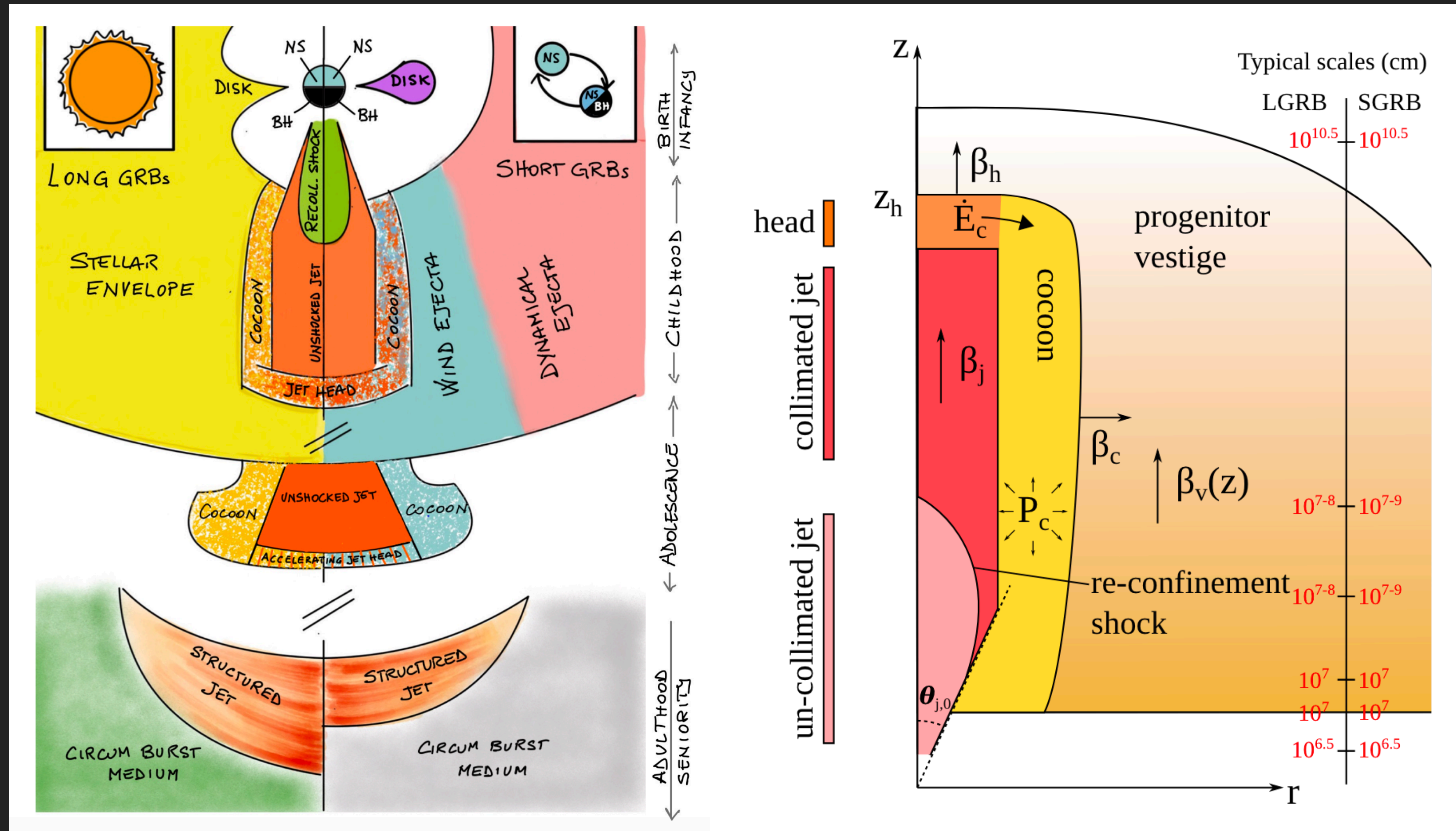
POINDRILA GHOSH

THE OSKAR KLEIN CENTRE FOR COSMOPARTICLE PHYSICS, STOCKHOLM UNIVERSITY

IMPACT OF AXION-LIKE PARTICLES ON GAMMA-RAY BURSTS

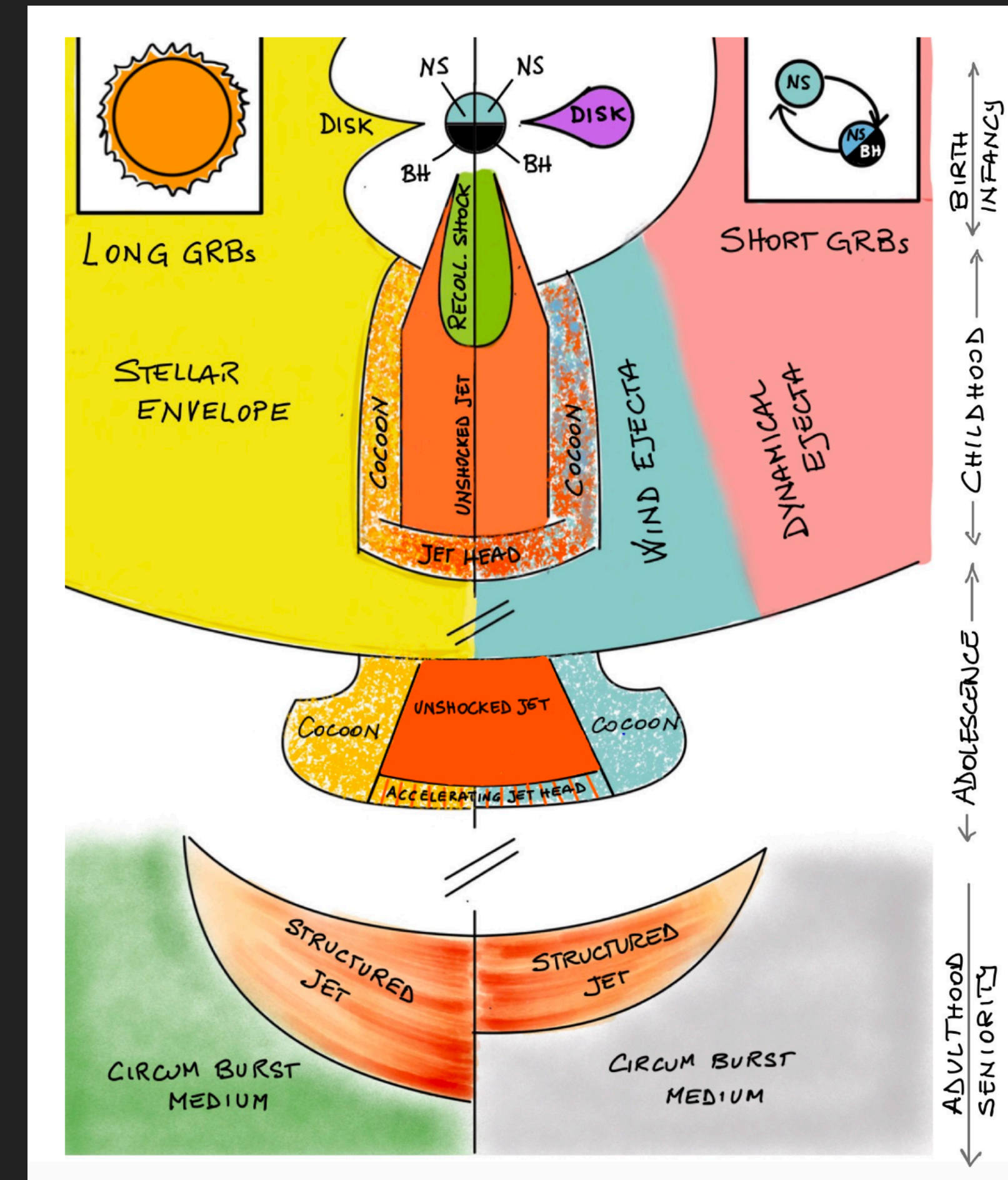
Dark Matter 2025, Santander | June 5, 2025

ANATOMY OF A FAST TRANSIENT



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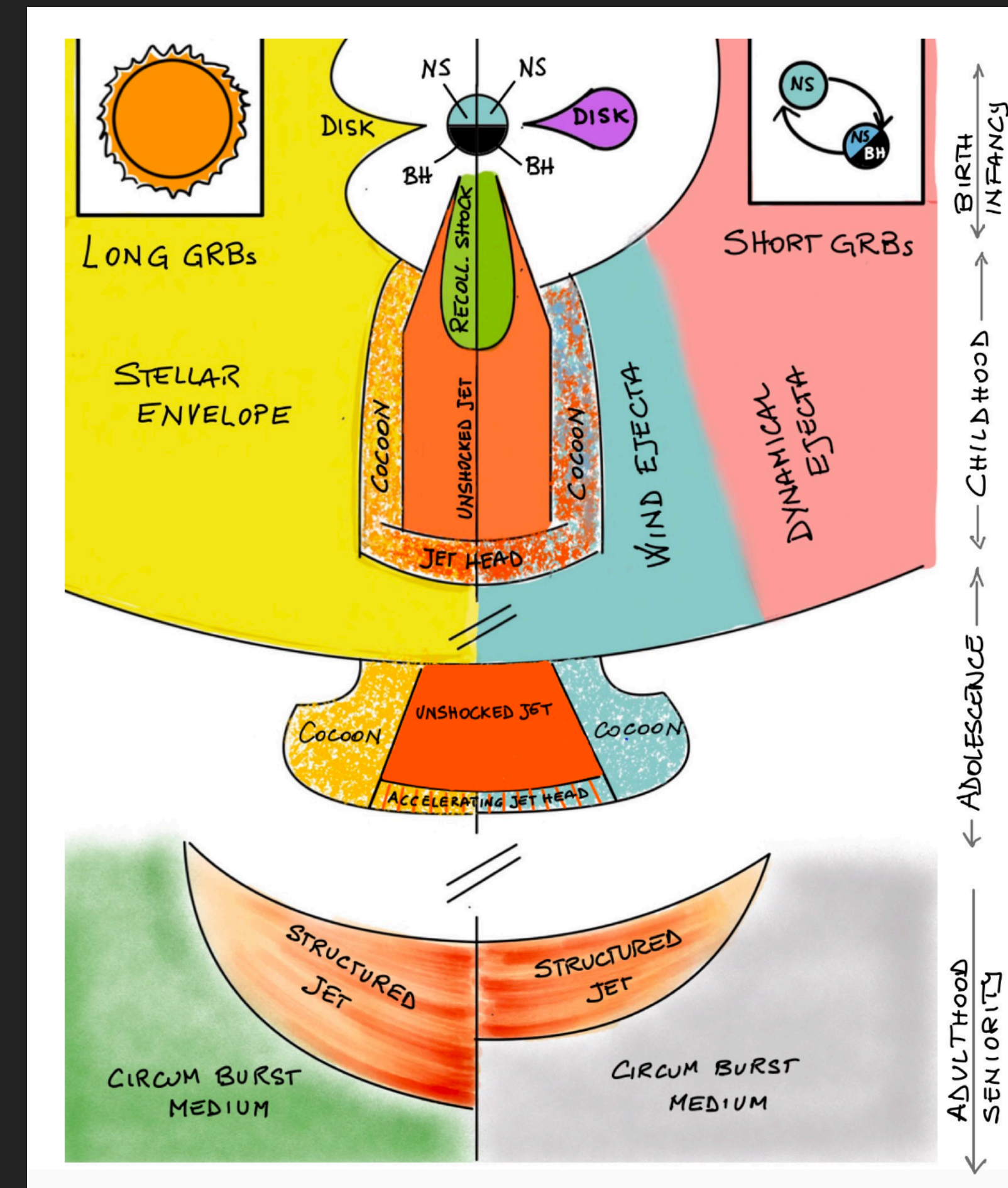
- ▶ Central engine: compact object/ merger remnant + accretion disk



Salafia & Ghirlanda, 2022

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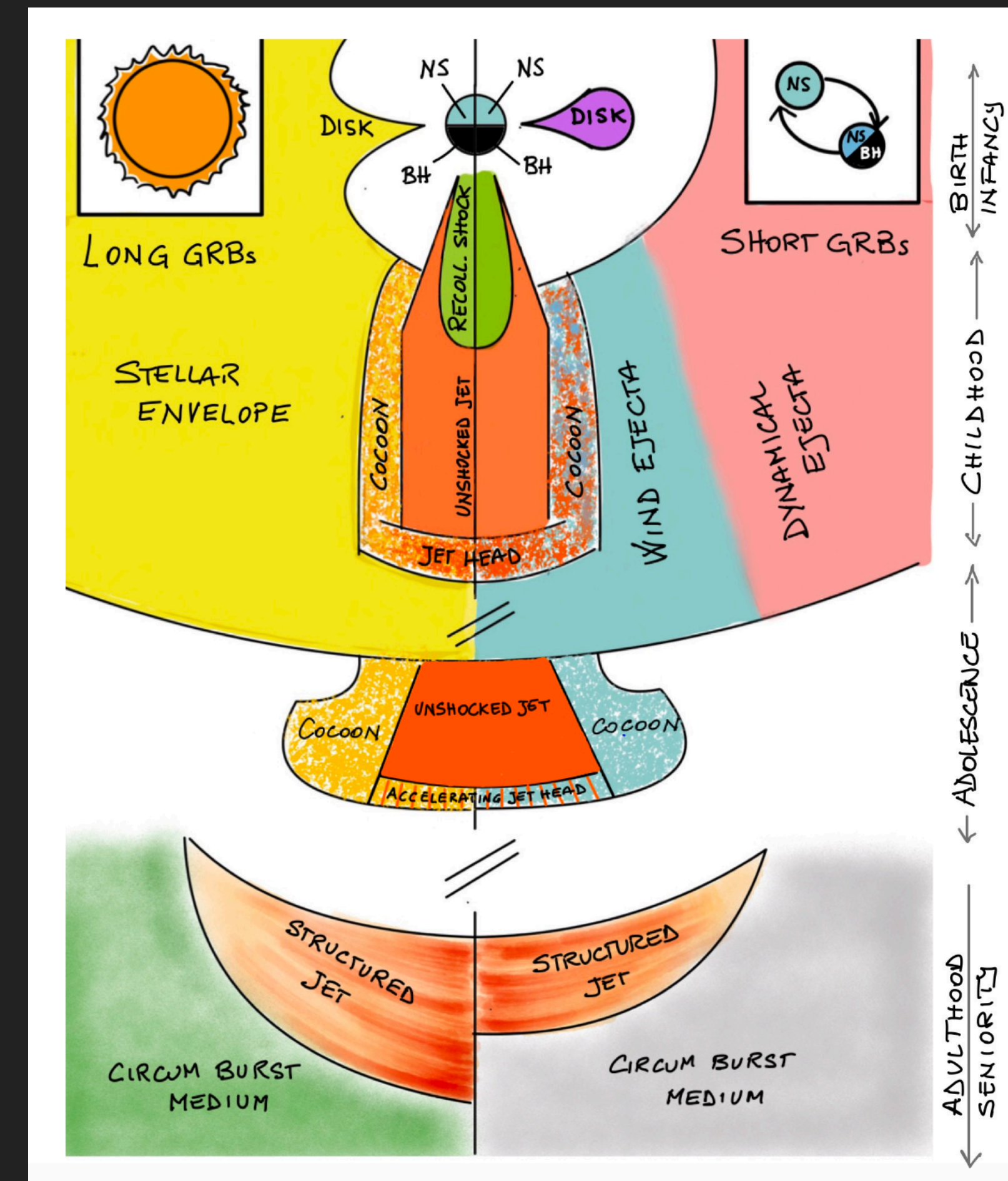
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- ▶ A bipolar relativistic collimated ejecta is launched



Salafia & Ghirlanda, 2022

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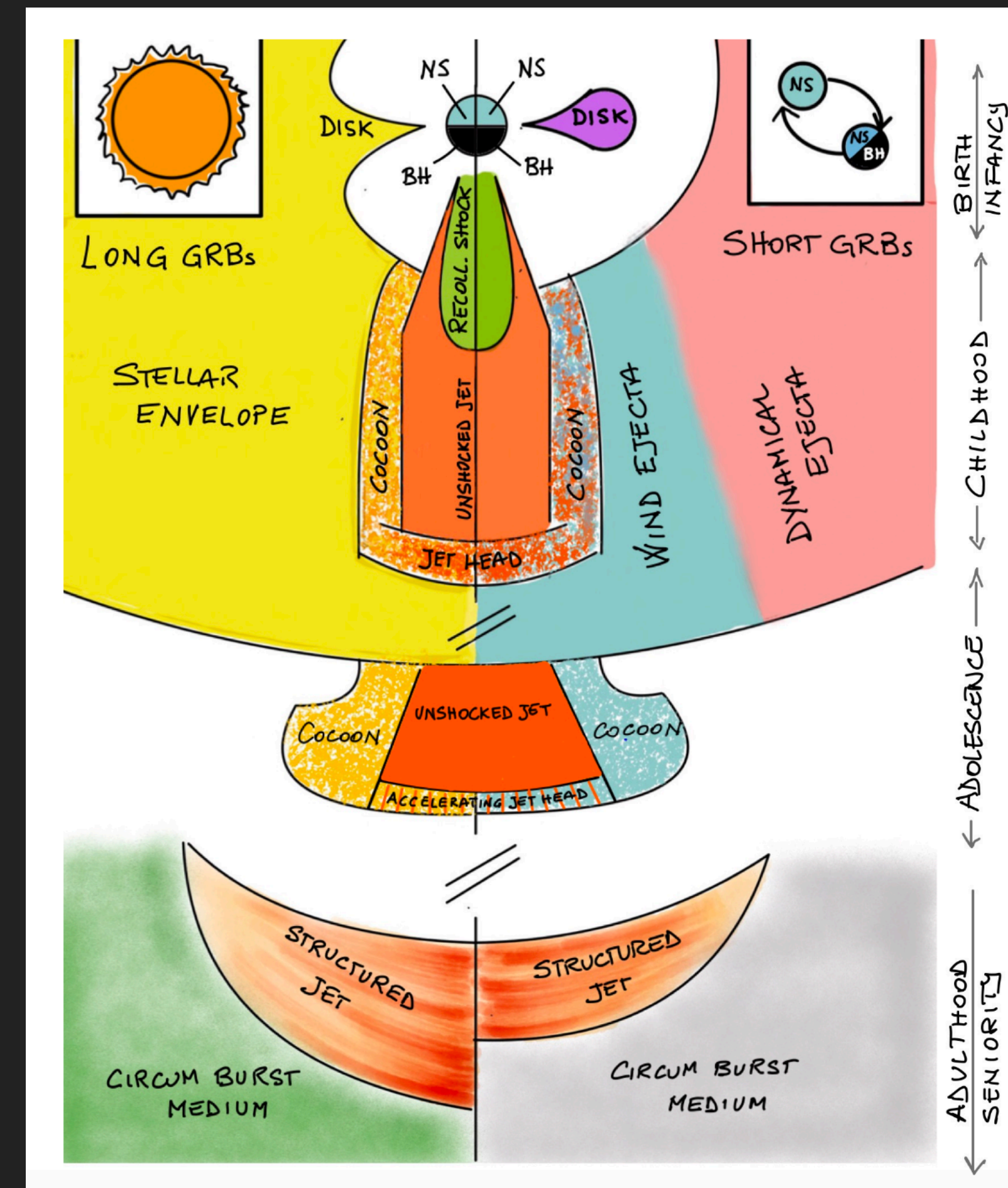
- ▶ Central engine: compact object/ merger remnant + accretion disk
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- ▶ Bulk energy dissipation leads to bright, highly variable, non-thermal prompt emission



Salafia & Ghirlanda, 2022

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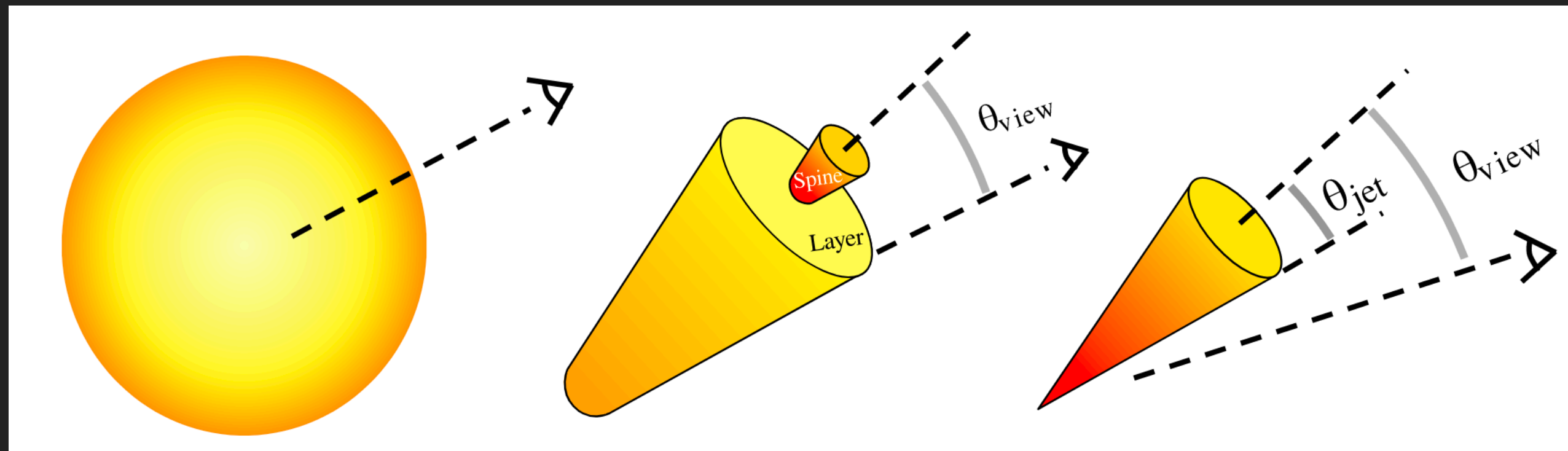
- ▶ Central engine: compact object/merger remnant + accretion disk
- ▶ A bipolar relativistic collimated ejecta is launched
- ▶ Bulk energy dissipation leads to bright, highly variable, non-thermal prompt emission
- ▶ The long-lasting multi-wavelength afterglow emission results from outflow interacting with the circumburst medium



Salafia & Ghirlanda, 2022

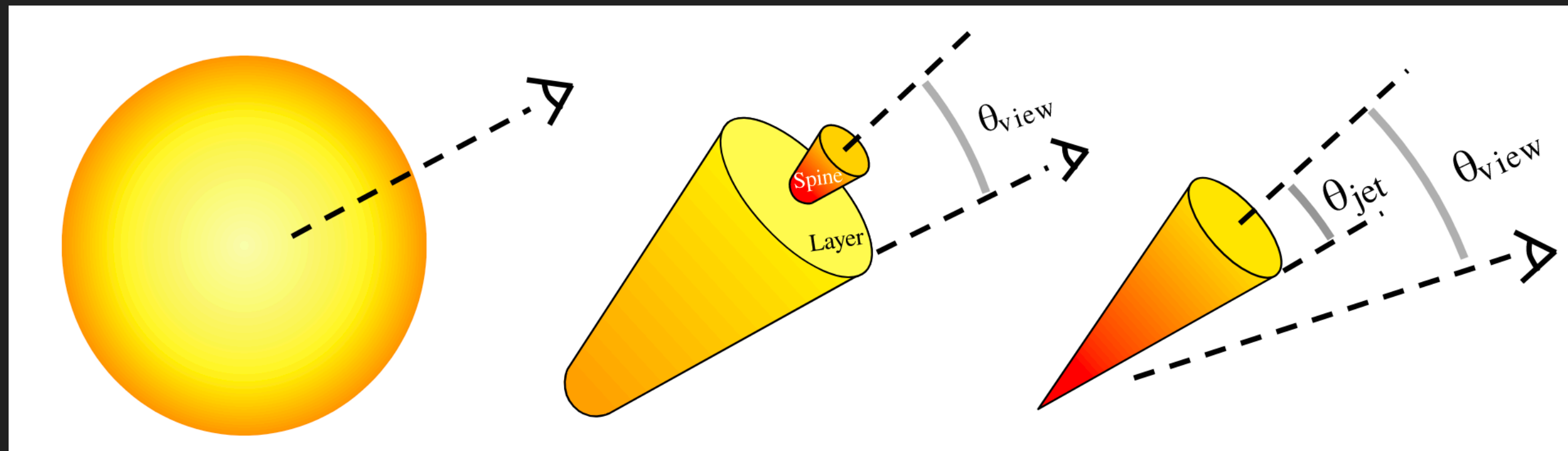
FIREBALL LAUNCH

- ▶ Several jetted and non-jetted models exist



Salafia, Ghisellini & Ghirlanda, 2022

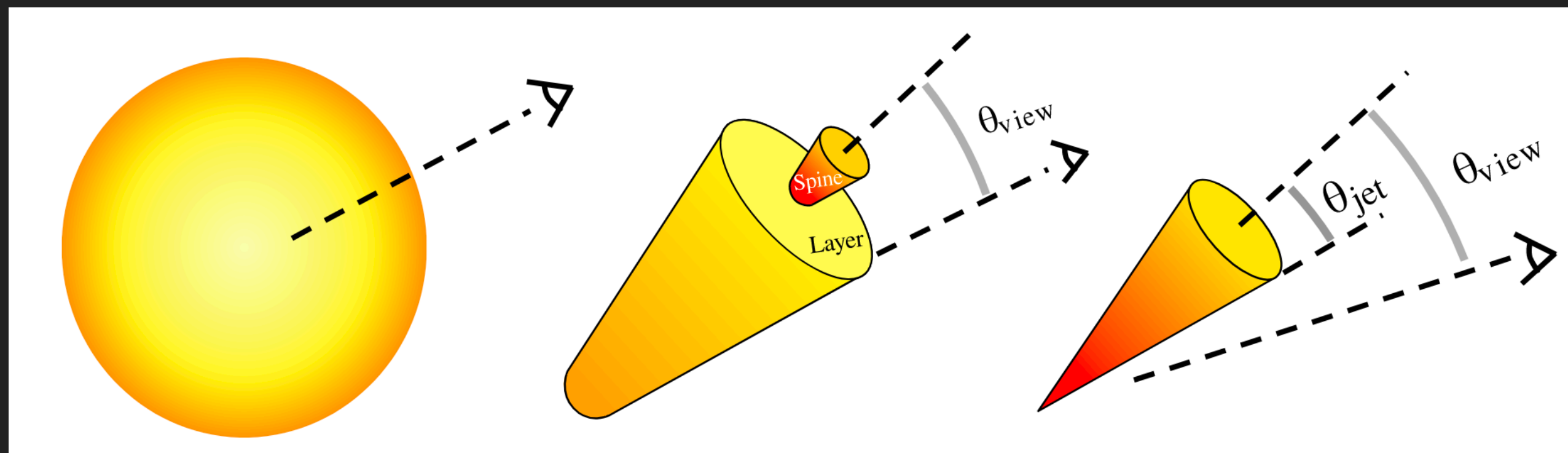
FIREBALL LAUNCH



Salafia, Ghisellini & Ghirlanda, 2022

- ▶ Several jetted and non-jetted models exist
- ▶ For structured jets, viewing angles play an important role in brightness estimation

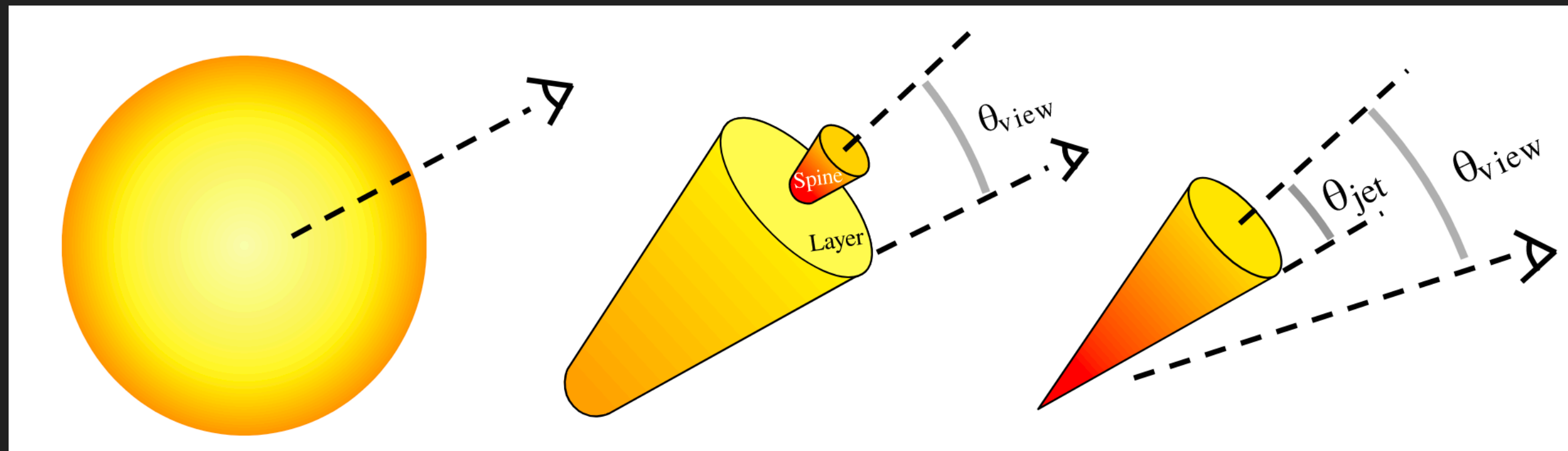
FIREBALL LAUNCH



Salafia, Ghisellini & Ghirlanda, 2022

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FIREBALL LAUNCH

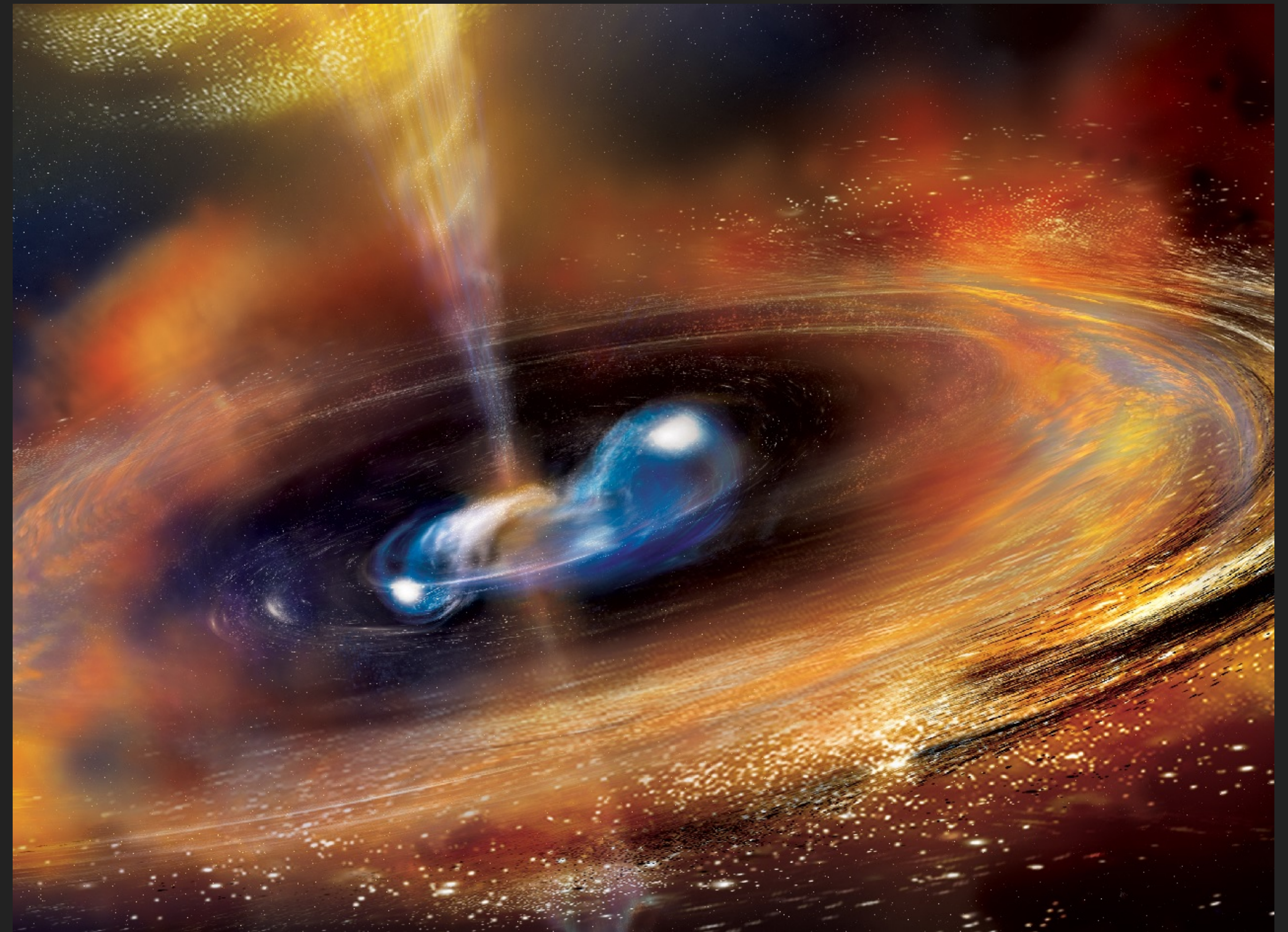


Salafia, Ghisellini & Ghirlanda, 2022

- ▶ Several jetted and non-jetted models exist
- ▶ For structured jets, viewing angles play an important role in brightness estimation
- ▶ When outflow is collimated within an angle θ , adjusting for the beaming factor $\theta^2/2$
- ▶ Isotropic luminosity can reach $10^{54} - 10^{55}$ erg/s, with low-luminosity GRBs indicating a choked/cocooned jet

ENERGY DISSIPATION

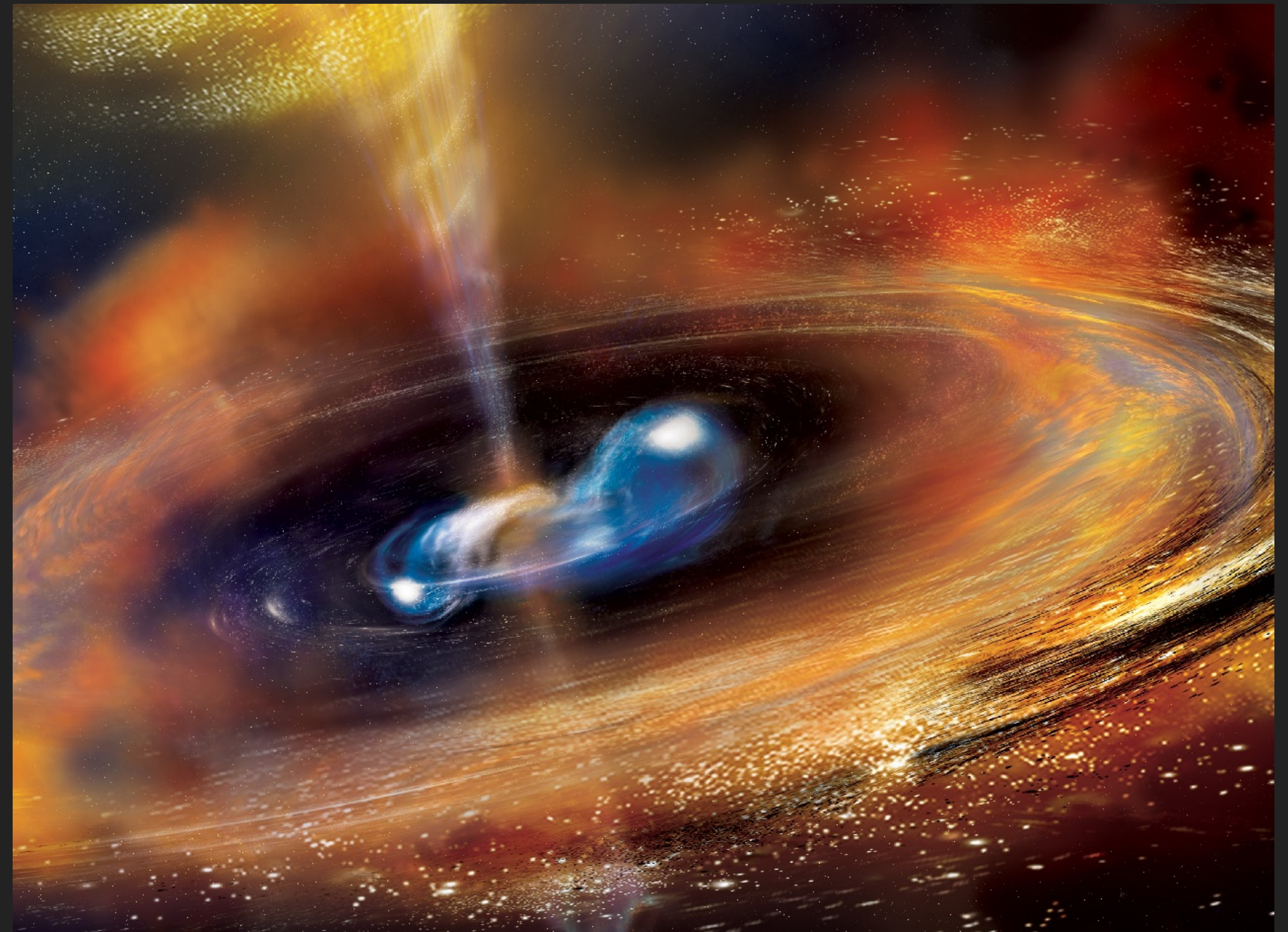
- ▶ Central engine: compact object mergers with gravitational wave counterparts



NASA

ENERGY DISSIPATION

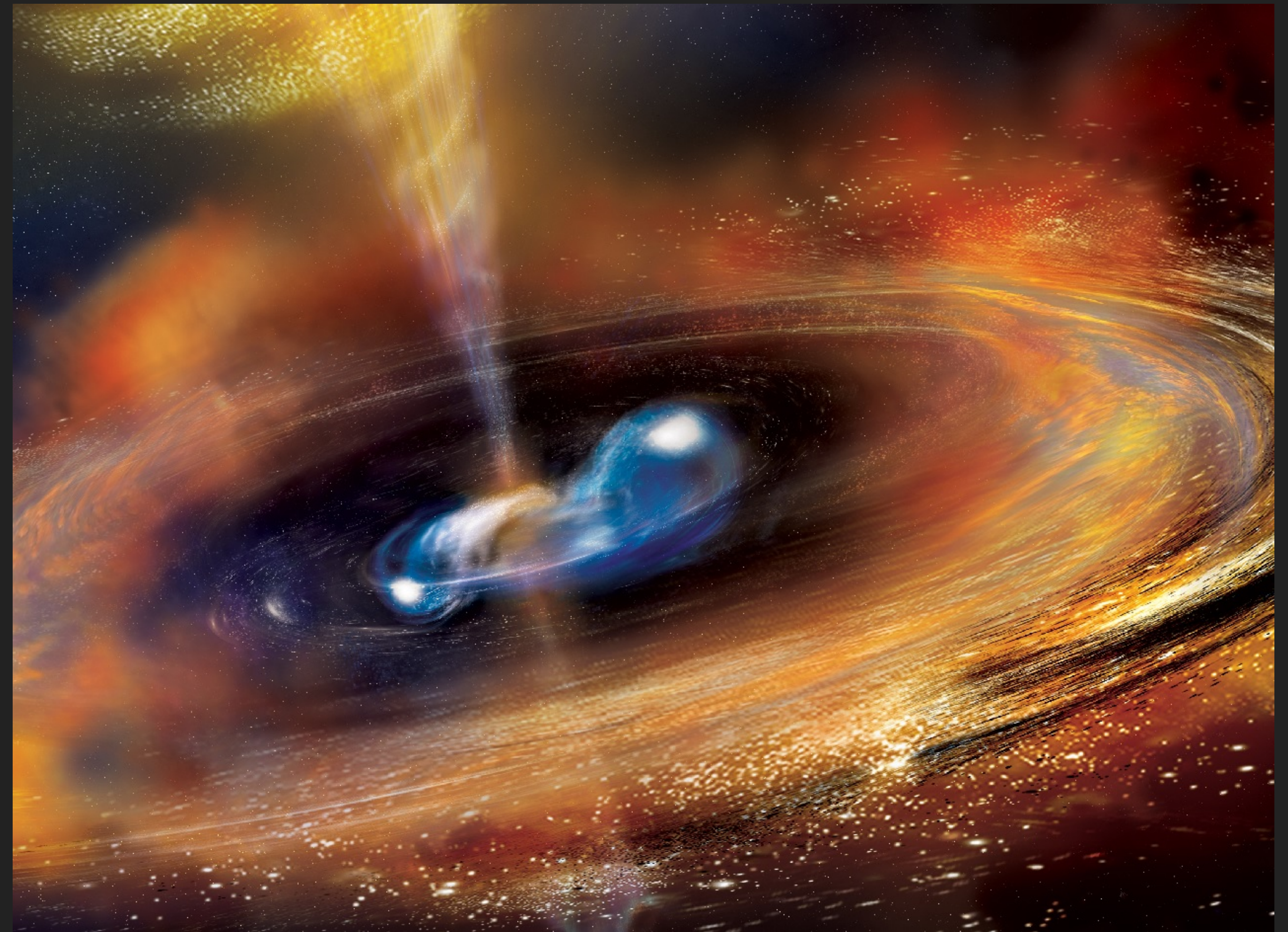
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- ▶ Average intrinsic luminosity for sGRBs $\sim 10^{50}$ erg/s



NASA

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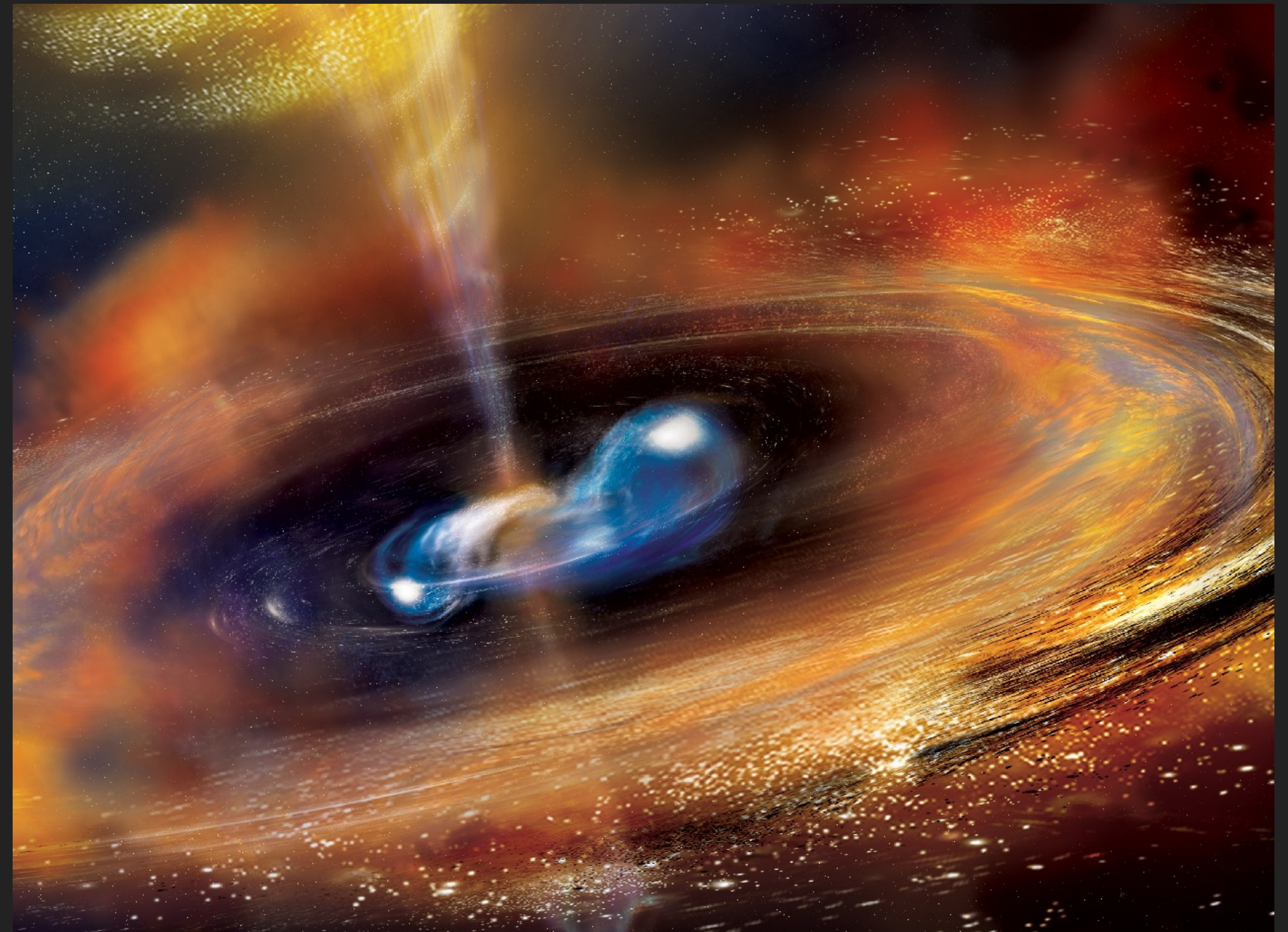
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NASA

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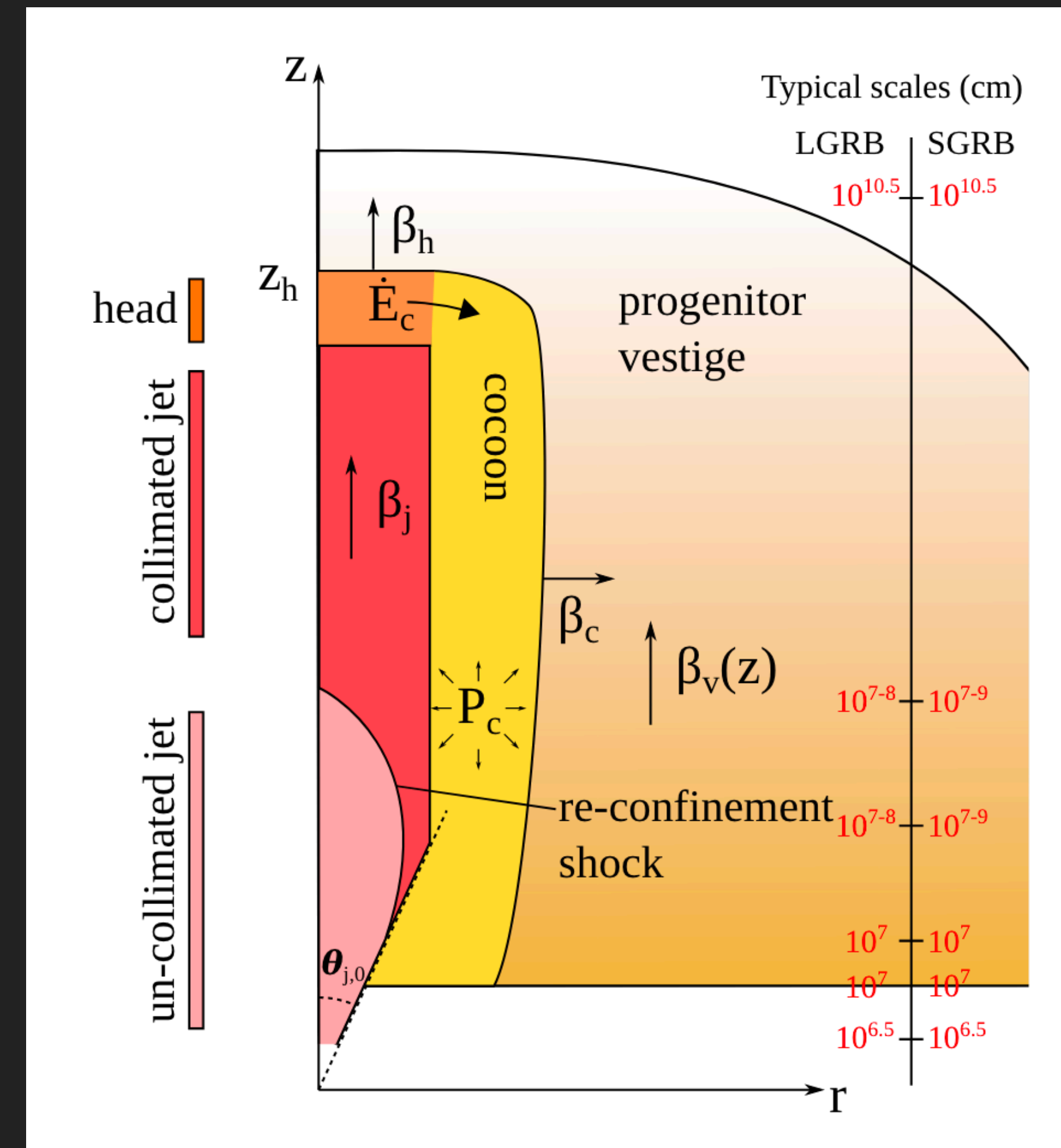
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- ▶ Hadronic scenario: created by neutrino-antineutrino annihilation



NASA

FIREBALL EVOLUTION

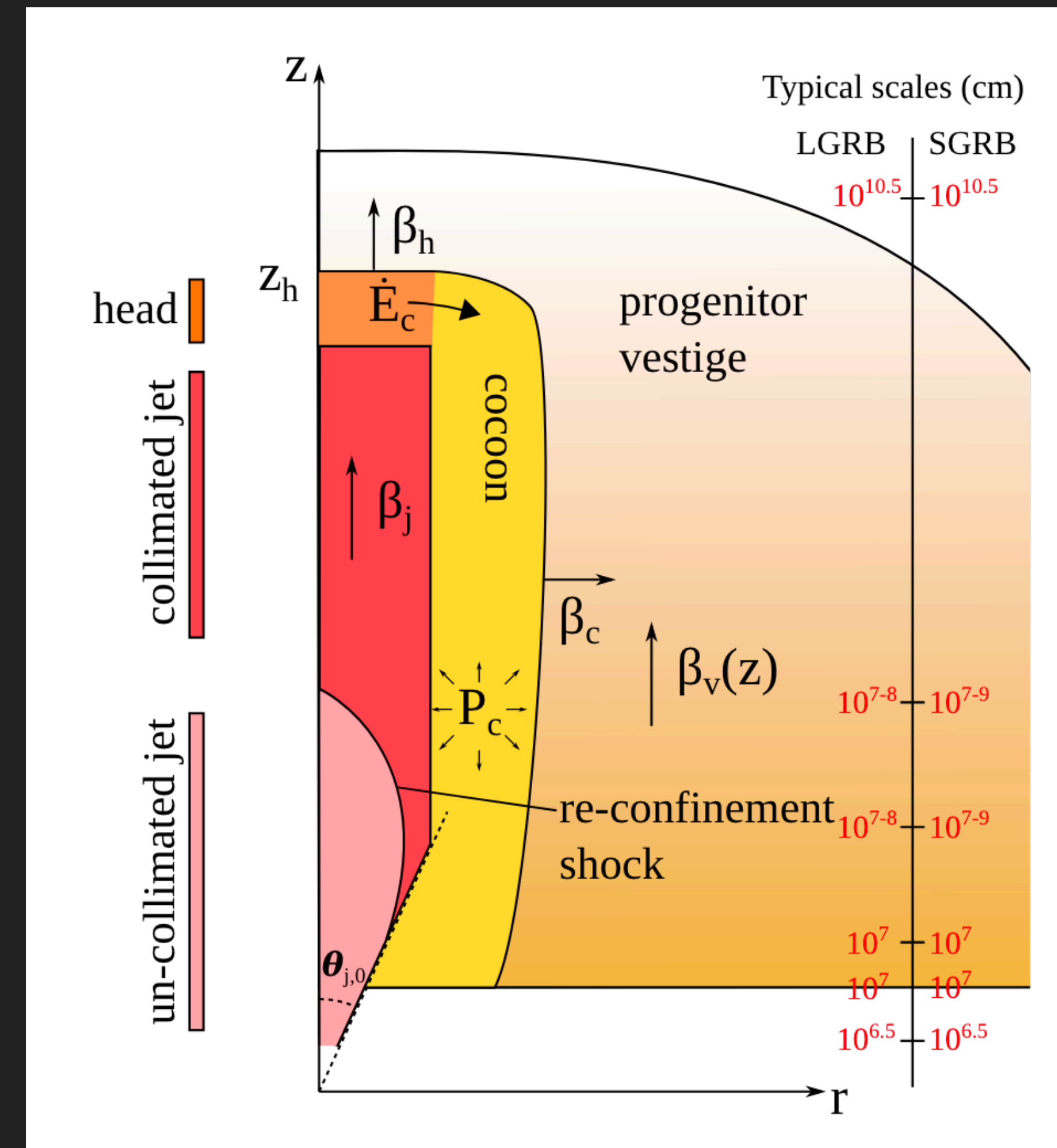
- ▶ A pure Radiation Fireball ($r \leq 10^8$ cm): Baryons negligible, fireball is radiation dominated: photon-lepton fireball



Salafia & Ghirlanda, 2022

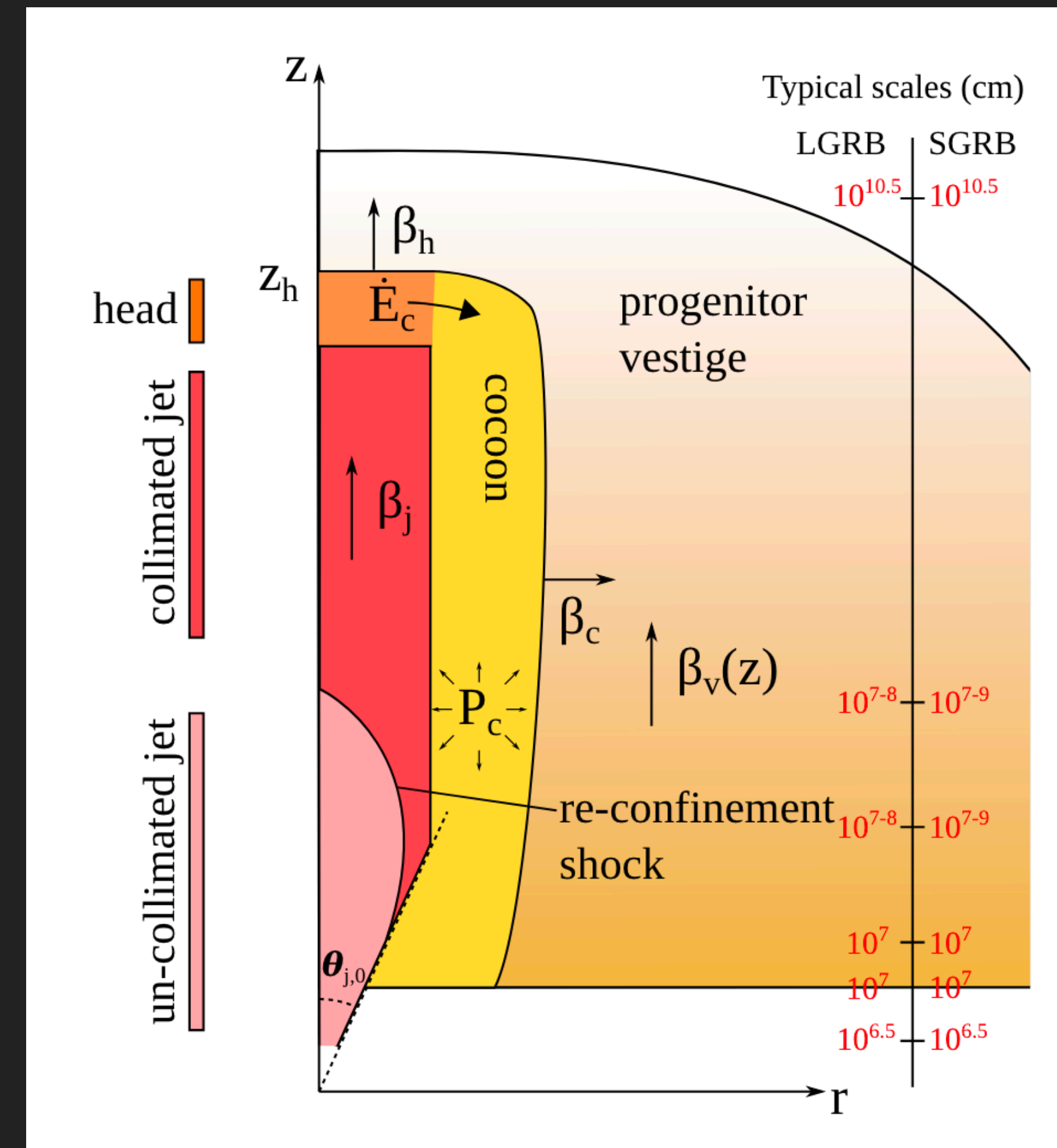
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- ▶ Relativistic Baryonic Fireball ($r \sim 10^9$ cm): Fireball is matter-dominated, as it re-thermalises swept-up mass. Internal energy converted into bulk kinetic energy of baryons, fireball decelerates
- ▶ Newtonian Fireball ($r > 10^9$ cm): Expansion is no longer relativistic. , e.g., energy deposition in the envelopes for SNe explosions



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THE PURELY RADIATIVE PHOTON-LEPTON FIREBALL

- ▶ A sphere with a characteristic injection radius r_0 and with a surface temperature T_0 would emit blackbody radiation at rate \dot{E} till the photosphere is reached

$$r_{ph} \gg r_0 \sim R_s$$

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$$r_{ph} \gg r_0 \sim R_s$$

- ▶ Temperature scaling $T = T_0 r_0 / r$

- ▶ Lorentz factor scaling $\gamma = r / r_0$

- ▶ Luminosity $\dot{E} = \frac{16}{3} 4\pi r_0^2 \sigma T_0^4$

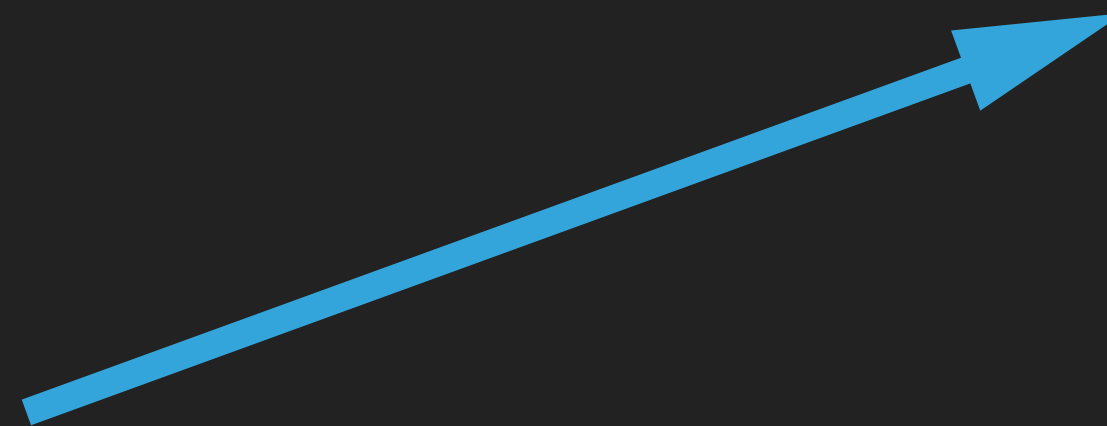
Solving Flammang's equation for a steady-state relativistic outflow

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL

GENERAL PRODUCTION MECHANISMS

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL

GENERAL PRODUCTION MECHANISMS



2 → 1 PROCESSES

HEAVY ALP PRODUCTION IN A LEPTONIC FIREBALL

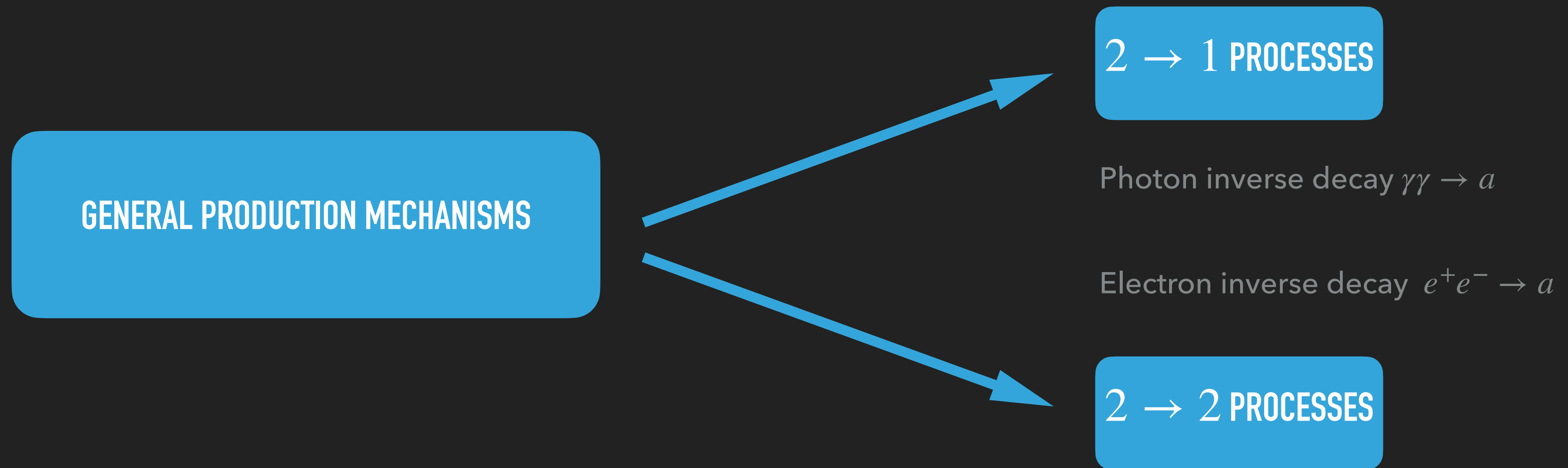
GENERAL PRODUCTION MECHANISMS

2 → 1 PROCESSES

Photon inverse decay $\gamma\gamma \rightarrow a$

Electron inverse decay $e^+e^- \rightarrow a$

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GENERAL PRODUCTION MECHANISMS

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graph LR; A[GENERAL PRODUCTION MECHANISMS] --> B[2 -> 1 PROCESSES]; A --> C[2 -> 2 PROCESSES];
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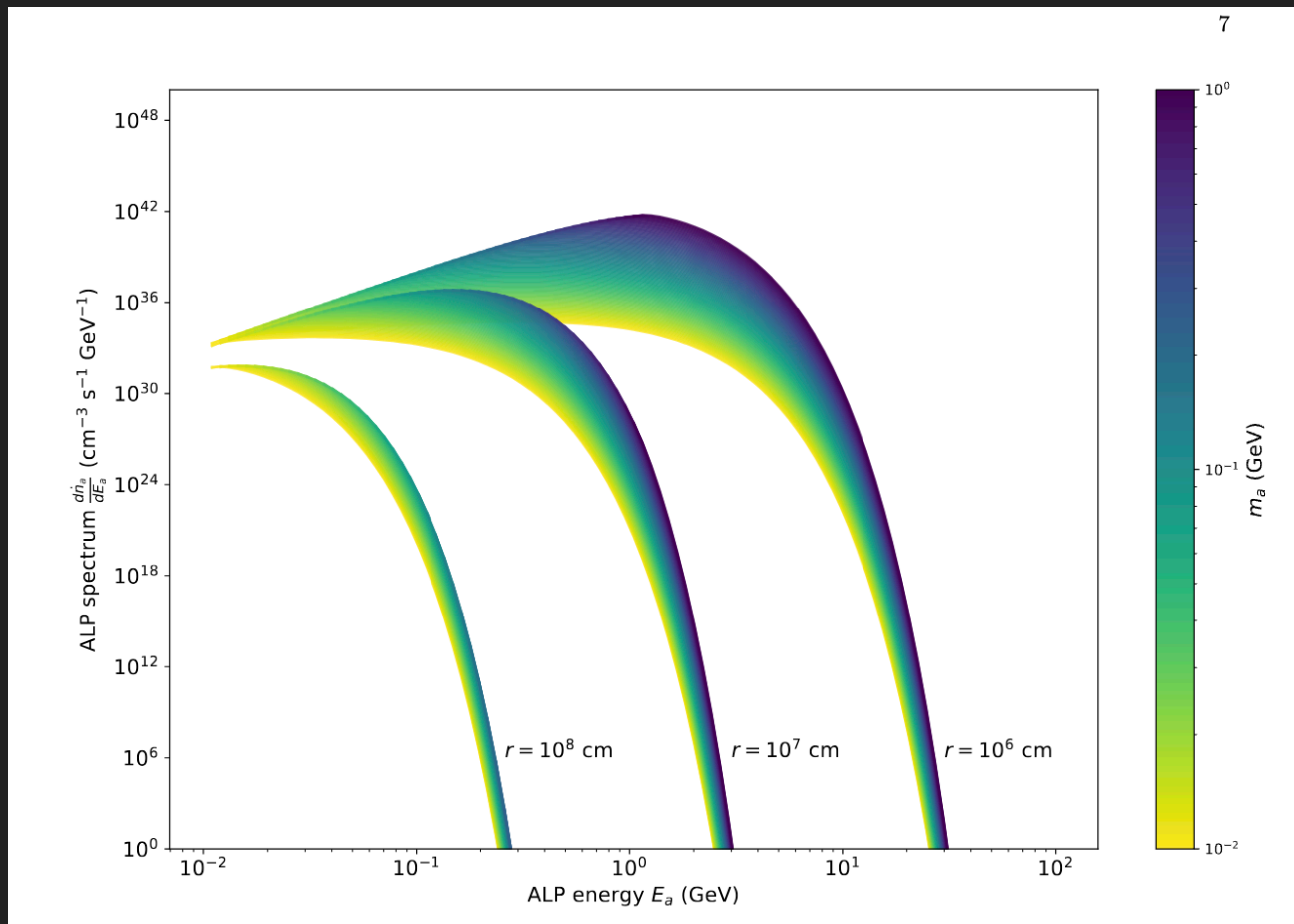
Electron inverse decay $e^+e^- \rightarrow a$

2 → 2 PROCESSES

Fermion annihilation $e^+e^- \rightarrow a + \gamma$

Photon conversion $e^\pm + \gamma \rightarrow e^\pm + a$

ALP SPECTRA IN LEPTONIC FIREBALLS



- ▶ Production depends on the radius (temperature) of the fireball

- ▶ Produced ALP spectra

$$\frac{dn_a}{dE_a}(r) = \frac{g_{a\gamma}^2}{128\pi^3} m_a^4 p \left(1 - \frac{4\omega_{\text{pl}}^2}{m_a^2}\right)^{3/2} e^{-E_a/T(r)}$$

OG, Jacobsen, Linden 2501.08978

STANDARD MODEL PROCESSES IN THE FIREBALL

▶ Bremsstrahlung rate $\Gamma_{\text{brem}} \approx \frac{2n_e \alpha^3 \log(e^{\gamma E} m_e^2 / T(r)^2)}{9m_e^2} \left[12 \log(e^{\gamma E} m_e^2 / T(r)^2) - 84 + 48 \log(e^{\gamma E} m_e / T(r)) \right]$ $ee \rightarrow eey$

▶ Annihilation rate $\Gamma_{\text{annih}} \approx \frac{\pi n_e \alpha^2}{m_e^2} \left(1 + \frac{2(T(r)/m_e)^2}{1 + \log\left(\frac{2T(r)}{m_e e^{\gamma E}} + 1.3\right)} \right)^{-1}$ $e^+e^- \rightarrow \gamma\gamma$

We assume $E_\gamma = T$

The mean photon energy taking on the thermal energy in the blackbody

▶ Pair production rate $\Gamma_{\text{prod}} = \begin{cases} 0, & T < 10m_e \\ n_\gamma \cdot \sigma_{\gamma\gamma \rightarrow e^+e^-} \cdot c, & T \geq 10m_e \end{cases}$ with

$$\sigma_{\gamma\gamma \rightarrow e^+e^-} = \frac{\pi \alpha^2}{E_\gamma^2} \left[\left(2 + \frac{2m_e^2}{E_\gamma^2} - \frac{m_e^4}{E_\gamma^4} \right) \right.$$

$$\left. \times \log \left| \frac{E_\gamma}{m_e} + \sqrt{\frac{E_\gamma^2}{m_e^2} - 1} \right| - \sqrt{1 - \frac{m_e^2}{E_\gamma^2}} \left(1 + \frac{m_e^2}{E_\gamma^2} \right) \right]$$

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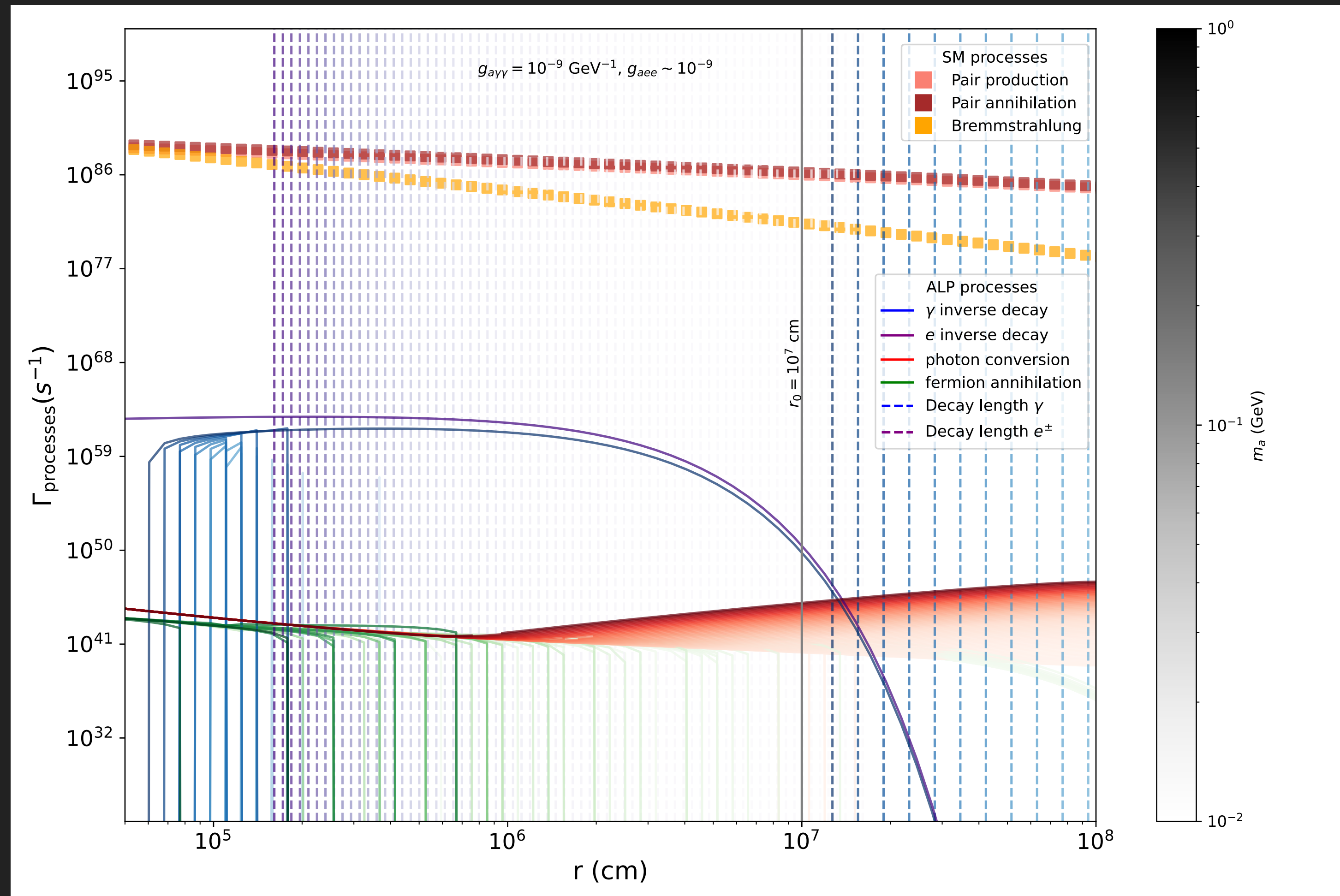
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ALPS BORN IN LEPTONIC FIREBALLS



- ▶ Fireball is launched at a distance scale from the central engine of the order of the Schwarzschild radius

$$R_s = \sqrt{\frac{2G}{c^2} \left(\frac{M}{3M_\odot} \right)} = 8.86 \times 10^5 \text{ cm}$$

- ▶ Most of the ALP production takes place before the fireball expands to its photospheric radius
- ▶ ALPs perform energy transport out of the fireball and decay outside

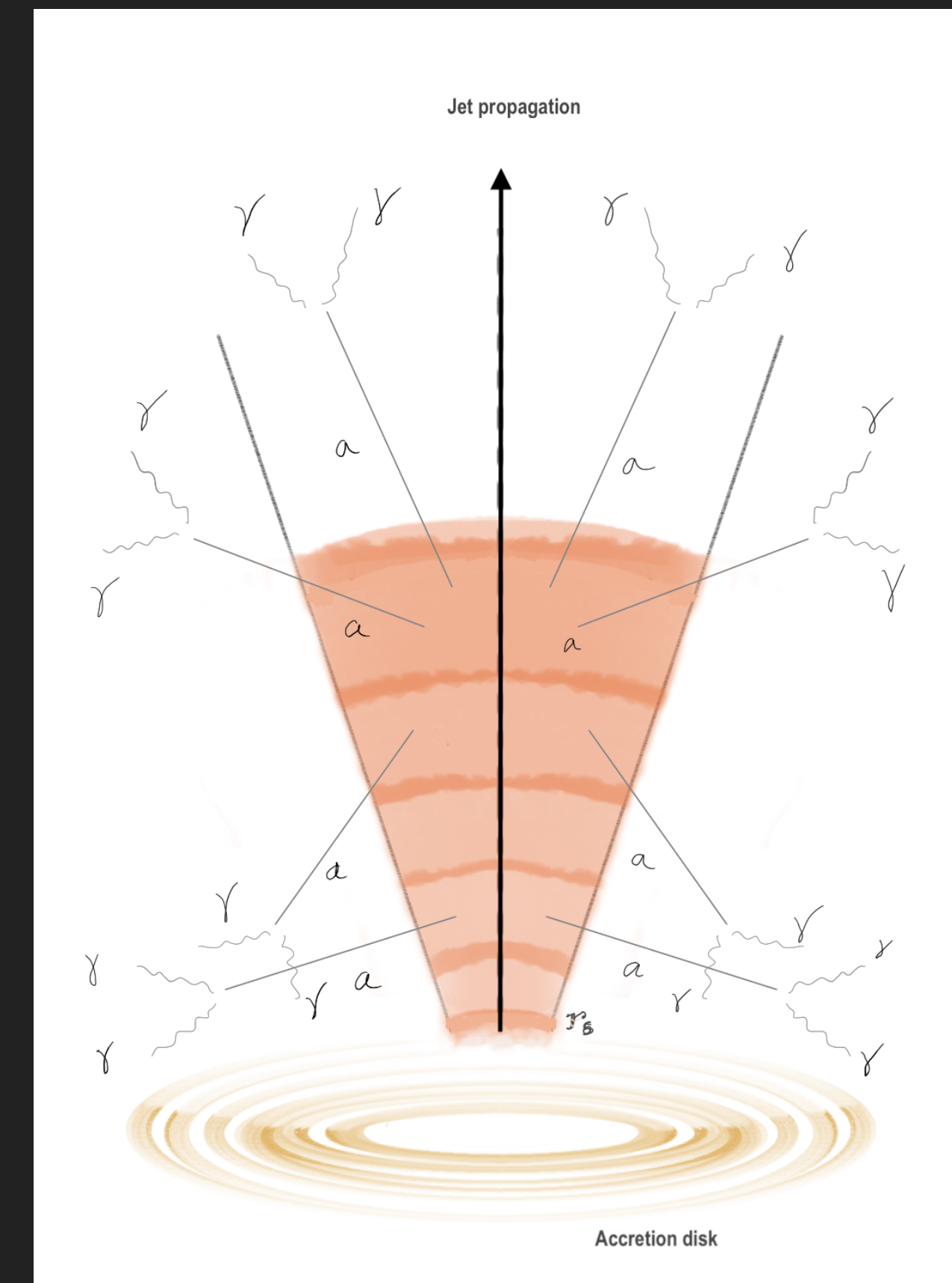
OG, Jacobsen, Linden (this work) 2501.08978

LUMINOSITY CALCULATION FOR A PHOTOPHILIC ALP

- ▶ Luminosity at production

$$L_{a,prod} = \pi \Delta \theta^2 \int_{r_s}^{R_c} dr r^2 \int_{m_a}^{\infty} dE E \frac{d\dot{n}_a(r)}{dE_a}$$

We set $R_c = 10^7$ cm



GRAVITATIONAL TRAPPING

- ▶ Accounting for gravitational trapping does not significantly alter our estimates

$$L_{a,prod} = \int \dots \Theta \left(E_a - m_a - \frac{2GMm_a}{rc^2} \right)$$

- ▶ Ejecta/ fireball expansion speed $\sim 0.3c - 0.6c$
- ▶ Boosted further by the fireball Lorentz factor in the observer frame
 $\Gamma_0 \sim 4/3$ at birth

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- ▶ Decay length

$$\lambda_{\gamma\gamma \rightarrow a} = \frac{64\pi}{g_{a\gamma}^2 m_a^4} \sqrt{E_a^2 - m_a^2}$$

- ▶ Decay-adjusted luminosity

$$L_{a,prod} = \int \dots \exp(-r/\lambda_{\gamma\gamma \rightarrow a})$$

- ▶ Average axion speed in the lab frame \gg fireball expansion speed

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r	T (GeV)	m_a (GeV)	$\langle \gamma_a \rangle$
$r_s(2M_\odot) = 5.93 \times 10^5 \text{ cm}$	0.506	0.01	100.984308
		0.08	12.935285
		0.2	5.551709
		0.5	2.713063
		1	1.817522
$r_s(3M_\odot) = 8.90 \times 10^5 \text{ cm}$	0.337	0.01	67.377468
		0.08	8.808573
		0.2	3.956192
		0.5	2.111106
		1	1.529511
$r_s(4M_\odot) = 1.19 \times 10^6 \text{ cm}$	0.253	0.01	50.584786
		0.08	6.765675
		0.2	3.174323
		0.5	1.817522
		1	1.385863
$r_c = 3.00 \times 10^7 \text{ cm}$	0.01	0.01	2.692544
		0.08	1.115430

Energies of ALPs produced at various radii(temperatures) and remnant masses

CAN THE FIREBALL EMERGE AGAIN?

Outside the source

- ▶ Mean free path of VHE photon in the circum-burst medium

$$\lambda_{mfp, \text{ decay}} = hc/E_{\gamma, \text{ decay}} = 1/(1 \text{ GeV}) \sim 10^{-14} \text{ cm}$$

- ▶ Critical number density required for decay photons from GeV-scale ALPs to thermalise via pair production outside

$$n_{cr} \sim 1/\left(\lambda_{mfp, \text{ decay}} \sigma_T\right) \sim 10^{38} \text{ cm}^{-3}$$

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Inside the source

- ▶ Mean free path of thermal photons

$$\lambda_{mfp, \text{ decay}} = hc/E_{\gamma, \text{ decay}} = 1/(100\text{MeV}) \sim 10^{-13} \text{ cm}$$

- ▶ Critical density needed for thermalisation

$$n_{cr} \sim 1/\left(\lambda_{mfp, \text{ th}} \sigma_T\right) \sim 10^{37} \text{ cm}^{-3}$$

- ▶ Inside fireball, thermal photons have density

$$n_{\gamma} = (16\pi\zeta(3))/(c^3h^3) (k_B T)^3 \approx 20.3(100\text{MeV})^3 \sim 10^{37} \text{ cm}^{-3}$$

CAN THE FIREBALL EMERGE AGAIN?

- ▶ For a burst duration of 10 ms, total number of ALP produced $\sim 10^{52}$
- ▶ For a GeV-scale ALP with decay length $\sim 10^7$ cm, number density of decay photons $N_{\gamma, \text{decay}} / \left(\frac{4}{3} \pi \lambda_{\text{decay}}^3 \right) \sim 10^{27} \text{ cm}^{-3}$

CAN THE FIREBALL EMERGE AGAIN?

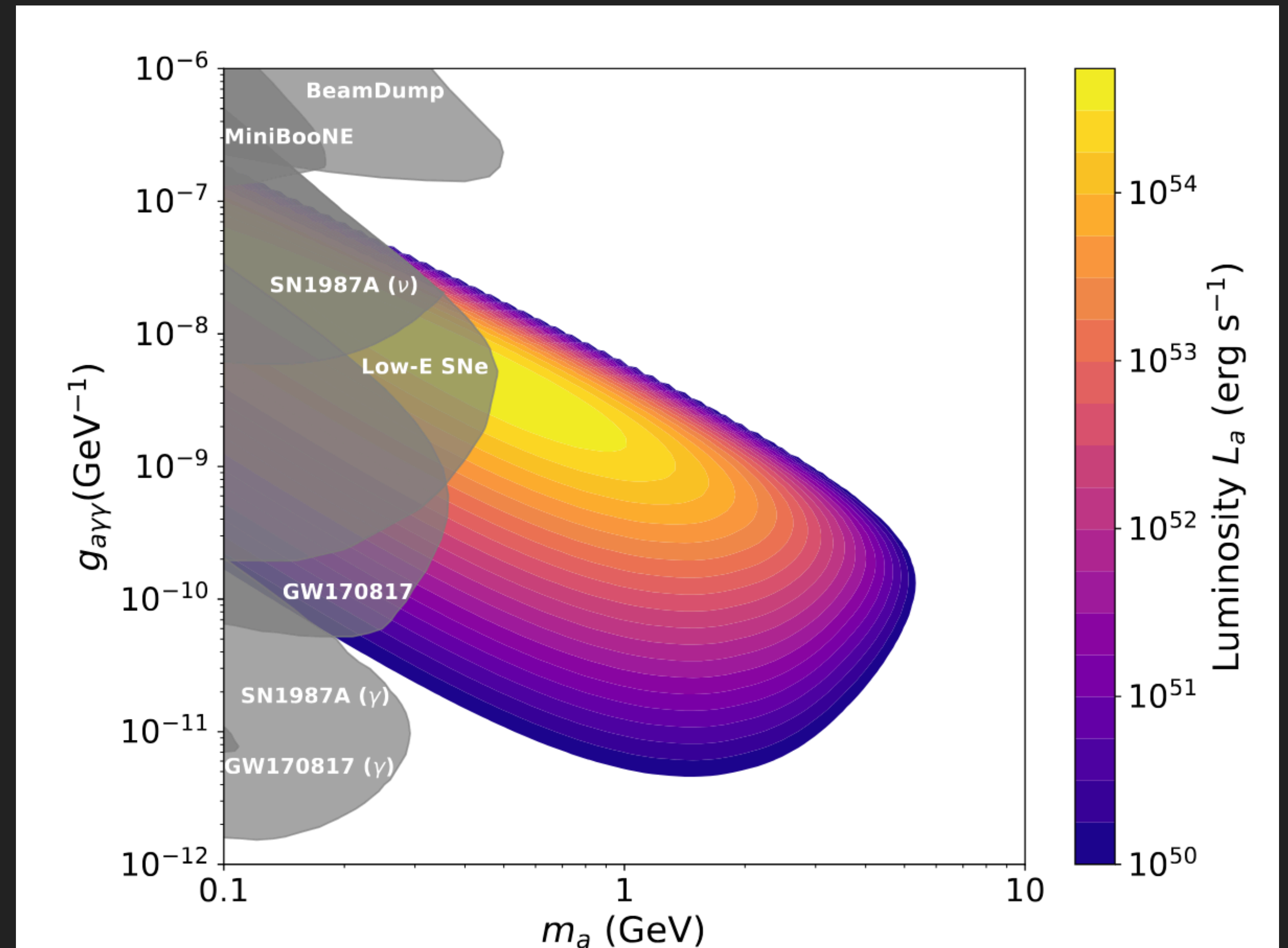
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UPON DECAY, THE PHOTOPHILIC ALPS PRODUCE A PHOTON FIELD TOO RAREFIED FOR THERMALISATION!

NO NEW FIREBALLS CAN FORM ONCE RADIATIVE TRANSFER OCCURS!

HEAVY AXIONS DISRUPT GAMMA-RAY BURSTS: STATE-OF-THE-ART BOUNDS

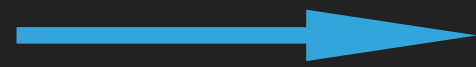
- ▶ We require $L_a \leq L_{intr} \sim 10^{50}$ erg/s for a complete disruption
- ▶ Calculated for a remnant mass of $3M_\odot$
- ▶ Assuming a conical geometry, less optimistic compared to an isotropically expanding fireball



OTHER CONSIDERATIONS

- ▶ Also applicable to AGNs that are flaring sources, with specific accretion flow solutions consistent with observations
- ▶ For parameter space leading to $L_a < \mathcal{O}(10^{50} \text{ erg/s})$, even if a fraction of the energy goes into axions, regular electromagnetic cascades can still take place
- ▶ Intergalactic magnetic field constraints from GRBs are significantly weakened
- ▶ For ALPs with nonzero electron and nucleon couplings, secondary decay e^+e^- pairs also participate in cascade

SUMMARY AND FUTURE

- ▶ We derive state-of-the-art limits down to $g_{a\gamma\gamma} \sim 4 \times 10^{-12} \text{GeV}^{-1}$ for ALP masses in the MeV-GeV scale
- ▶ Nonlinear feedback on IGMF limits due to ALP processes
- ▶ Comprehensive treatment which also applies to fireballs with baryon loading
- ▶ Particularly interesting for sources associated with neutrino and GW events
- ▶ Primary and secondary decay products contribute to various diffuse photon backgrounds  watch out for excesses!

Thank you!

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